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SUSY Particle Production at Hadron Colliders*

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Abstract

The determination of the full SUSY QCD corrections to the production of squarks, gluinos and gauginos at hadron colliders is reviewed. The NLO corrections stabilize the theoretical predictions of the various production cross sections significantly and lead to sizeable enhancements of the most relevant cross sections. We discuss the phenomenological consequences of the results on present and future experimental analyses.

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1 Introduction

The search for Higgs bosons and supersymmetric particles is among the most important endeavors of present and future high energy physics. The novel colored particles, squarks and gluinos, and the weakly interacting gauginos can be searched for at the upgraded Tevatron, a $p\bar{p}$ collider with a c.m. energy of 2 TeV, and the LHC, a pp collider with a c.m. energy of 14 TeV. Until now the search at the Tevatron has set the most stringent bounds on the colored SUSY particle masses. At the 95% CL, gluinos have to be heavier than about 180 GeV, while squarks with masses below about 180 GeV have been excluded for gluino masses below ~ 300 GeV [1]. Stops, the scalar superpartners of the top quark, have been excluded in a significant part of the MSSM parameter space with mass less than about 80 GeV by the LEP and Tevatron experiments [1]. Finally charginos with masses below about 90 GeV have been excuded by the LEP experiments, while the present search at the Tevatron is sensitive to chargino masses of about 60–80 GeV with a strong dependence on the specific model [1]. Due to the negative search at LEP2 the lightest neutralino $\tilde{\chi}_1^0$ has to be heavier than about 30 GeV in the context of SUGRA models [1]. In the R-parity-conserving MSSM, supersymmetric particles can only be produced in pairs. All supersymmetric particles will decay to the lightest supersymmetric particle (LSP), which is most likely to be a neutralino, stable thanks to conserved R-parity. Thus the final signatures for the production of supersymmetric particles will mainly be jets, charged leptons and missing transverse energy, which is carried away by neutrinos and the invisible neutral LSP.

In Section 2 we shall summarize the details of the calculation of the NLO QCD corrections, as described in Refs. [2–4] for the case of $\tilde{q}\bar{\tilde{q}}$ production. The

evaluation of the full SUSY QCD corrections splits into two pieces, the virtual corrections, generated by virtual particle exchanges, and the real corrections, which originate from gluon radiation and the corresponding crossed processes with three-particle final states.

In Section 3 we shall consider the production of squarks and gluinos except stops [2]. We assume the light-flavored squarks to be mass degenerate, which is a reasonable approximation for all squark flavors except stops, while the light quarks (u, d, s, c, b) will be treated as massless particles. The production of stop pairs requires the inclusion of mass splitting and mixing effects [3] and will be investigated in Section 4. In Section 5 we will summarize the results for the production of charginos and neutralinos at NLO [4]. The calculation of the LO cross sections has been performed a long time ago [5]. Since the [unphysical] scale dependence of the LO quantities amounts up to about 50%, the determination of the NLO corrections is necessary in order to gain a reliable theoretical prediction, which can be used in present and future experimental analyses.

2 SUSY QCD corrections

2.1 Virtual corrections

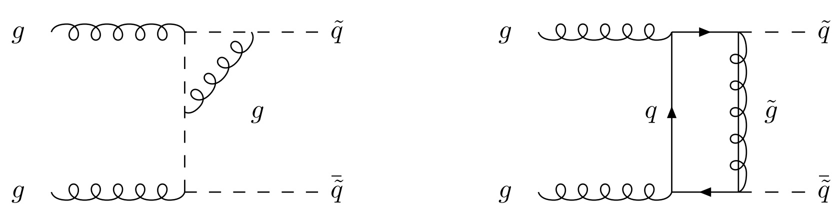

Figure 1: *Typical diagrams of the virtual corrections.*

The one-loop virtual corrections are built up by gluon, gluino, quark and squark exchange contributions [see Fig. 1]. They have to be contracted with the LO matrix elements. The calculation of the one-loop contributions has been performed in dimensional regularization, leading to the extraction of ultraviolet, infrared and collinear singularities as poles in $\epsilon = (4 - n)/2$. For the chiral γ_5 coupling we have used the naive scheme, which is well justified in the present analysis at the one-loop level[§]. We have explicitly checked that

[§]We have explicitely checked that the results obtained with a consistent γ_5 scheme are identical to the one with the naive scheme.

after summing all virtual corrections no quadratic divergences are left over, in accordance with the general property of supersymmetric theories. The renormalization has been performed by identifying the squark and gluino masses with their pole masses, and defining the strong coupling in the $\overline{\rm MS}$ scheme including five light flavors in the corresponding β function. The massive particles, i.e. squarks, gluinos and top quarks, have been decoupled by subtracting their contribution at vanishing momentum transfer [6]. In dimensional regularization, there is a mismatch between the gluonic degrees of freedom [d.o.f. $= n-2$] and those of the gluino [d.o.f. $=2$], so that SUSY is explicitly broken. In order to restore SUSY in the physical observables in the massless limit, an additional finite counter-term is required for the renormalization of the novel $\tilde{q}\tilde{g}\bar{q}$ vertex [7].

2.2 Real corrections

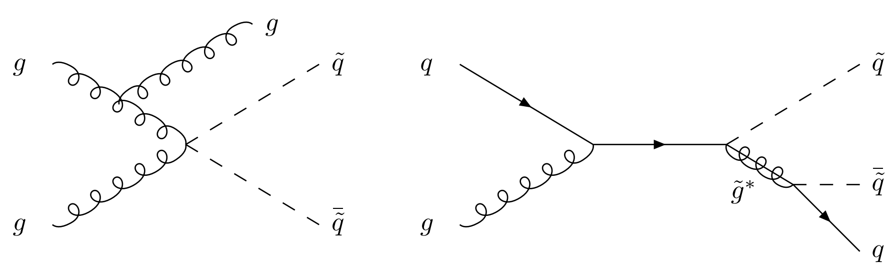

Figure 2: *Typical diagrams of the real corrections.*

The real corrections originate from the radiation of a gluon in all possible ways and from the crossed processes by interchanging the gluon of the final state against a light quark in the initial state. The phase-space integration of the final-state particles has been performed in $n = 4 - 2\epsilon$ dimensions, leading to the extraction of infrared and collinear singularities as poles in ϵ. After evaluating all angular integrals and adding the virtual and real corrections, the infrared singularities cancel. The left-over collinear singularities are universal and are absorbed in the renormalization of the parton densities at NLO. We defined the parton densities in the conventional $\overline{\rm MS}$ scheme including five light flavors, i.e. the squark, gluino and top quark contributions are not included in the mass factorization. Finally we end up with an ultraviolet, infrared and collinear finite partonic cross section.

However, there is an additional class of physical singularities, which have to be regularized. In the second diagram of Fig. 2 an intermediate $\tilde{q}\tilde{g}^*$ state is produced, before the [off-shell] gluino splits into a $q\bar{\tilde{q}}$ pair. If the gluino

mass is larger than the common squark mass, and the partonic c.m. energy is larger than the sum of the squark and gluino masses, the intermediate gluino can be produced on its mass-shell. Thus the real corrections to $\tilde{q}\bar{\tilde{q}}$ production contain a contribution of $\tilde{q}\tilde{g}$ production. The residue of this part corresponds to $\tilde{q}\tilde{g}$ production with the subsequent gluino decay $\tilde{g} \to \bar{\tilde{q}}q$, which is already contained in the LO cross section of $\tilde{q}\tilde{g}$ pair production, including all final-state cascade decays. This term has to be subtracted in order to derive a well-defined production cross section. Analogous subtractions emerge in all reactions: if the gluino mass is larger than the squark mass, the contributions from $\tilde{g} \to \tilde{q}\bar{q}, \bar{\tilde{q}}q$ have to be subtracted, and in the reverse case the contributions of squark decays into gluinos have to subtracted.

3 Production of Squarks and Gluinos

Squarks and gluinos can be produced via $pp, p\bar{p} \to \tilde{q}\bar{\tilde{q}}, \tilde{q}\tilde{q}, \tilde{q}\tilde{g}, \tilde{g}\tilde{g}$ at hadron colliders. The hadronic squark and gluino production cross sections can be obtained from the partonic ones by convolution with the corresponding parton densities. We have performed the numerical analysis for the upgraded Tevatron and the LHC. For the natural renormalization/factorization scale choice $Q = m$, where m denotes the average mass of the final-state SUSY particles, the SUSY QCD corrections are large and positive, increasing the total cross sections by 10–90% [2]. This is shown in Fig. 3, where the K factors, defined as the ratios of the NLO and LO cross sections, are presented as a function of the corresponding SUSY particle mass for the Tevatron. We have investigated

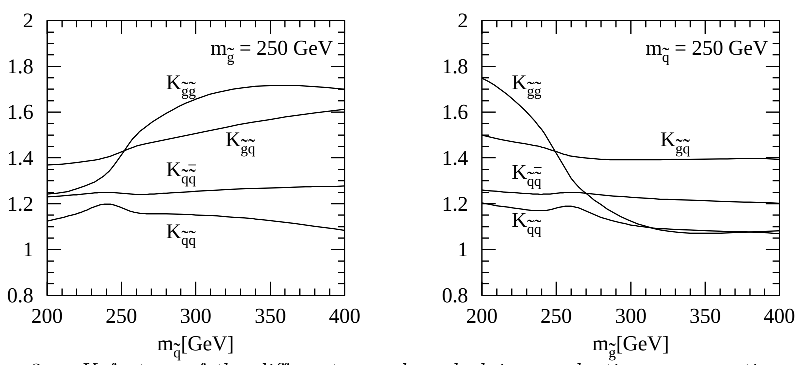

Figure 3: *K factors of the different squark and gluino production cross sections at the upgraded Tevatron [$\sqrt{s} = 2$ TeV]. Parton densities: CTEQ4L (LO) and CTEQ4M (NLO) with $Q = m$. Top mass: $m_t = 175$ GeV.*

the residual scale dependence in LO and NLO, which is presented in Fig. 4. The inclusion of the NLO corrections reduces the LO scale dependence by a

factor 3–4 and reaches a typical level of $\sim 15\%$, which serves as an estimate of the remaining theoretical uncertainty. Moreover, the dependence on different sets of parton densities is rather weak and leads to an additional uncertainty of $\sim 15\%$. In order to quantify the effect of the NLO corrections on the search for squarks and gluinos at hadron colliders, we have extracted the SUSY particle masses corresponding to several fixed values of the production cross sections. These masses are increased by 10–30 GeV at the Tevatron and 10–50 GeV at the LHC, thus enhancing the present and future bounds on the squark and gluino masses significantly. Finally we have evaluated the QCD-corrected

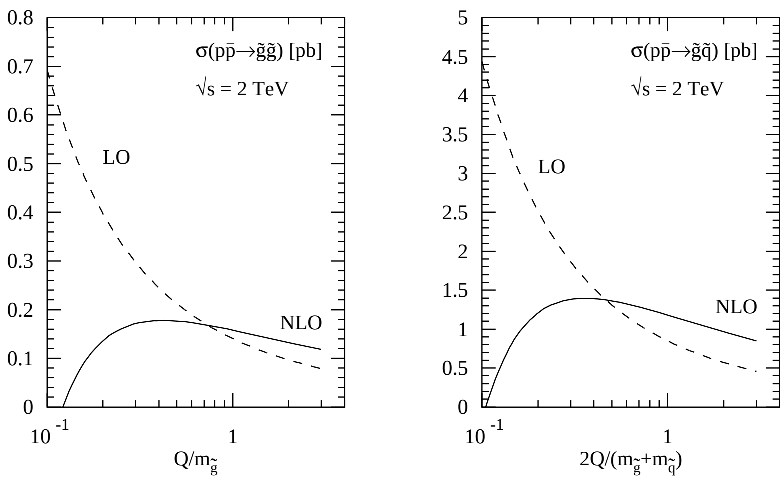

Figure 4: *Scale dependence of the total squark and gluino production cross sections at the Tevatron in LO and NLO. Parton densities: CTEQ4L (LO) and CTEQ4M (NLO); mass parameters: $m_{\tilde{q}} = 250$ GeV, $m_{\tilde{g}} = 300$ GeV and $m_t = 175$ GeV.*

transverse-momentum and rapidity distributions for all different processes. As can be inferred from Fig. 5, the modification of the normalized distributions in NLO compared to LO is less than about 15% for the transverse-momentum distributions and much less for the rapidity distributions. Thus it is a sufficient approximation to rescale the LO distributions uniformly by the K factors of the total cross sections.

4 Stop Pair Production

At LO only pairs of $\tilde{t}_1$ or pairs of $\tilde{t}_2$ can be produced at hadron colliders. Mixed $\tilde{t}_1\tilde{t}_2$ pair production is only possible at NLO and beyond. However, we have estimated that mixed stop pair production is completely suppressed by several orders of magnitude and can thus safely be neglected [3]. The evaluation of the

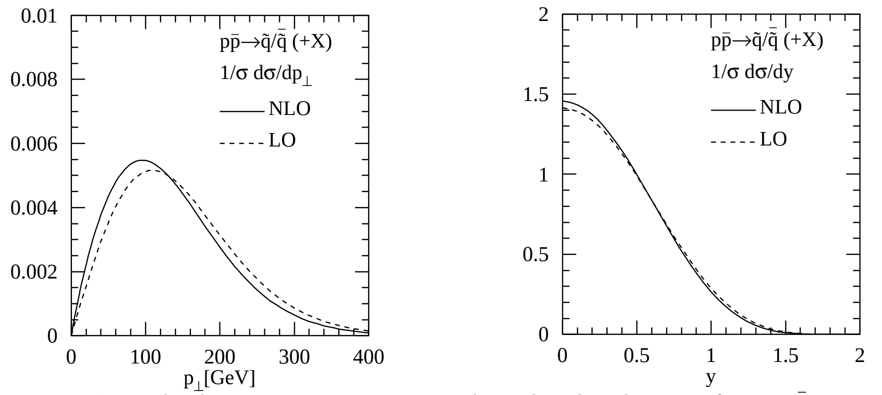

Figure 5: *Normalized transverse-momentum and rapidity distributions of $p\bar{p} \to \tilde{q}\bar{\tilde{q}} + X$ at the upgraded Tevatron [$\sqrt{s} = 2$ TeV] in LO (dotted) and NLO (solid). Parton densities: CTEQ4L (LO) and CTEQ4M (NLO) with $Q = m$; mass parameters: $m_{\tilde{q}} = 250$ GeV, $m_{\tilde{g}} = 300$ GeV and $m_t = 175$ GeV.*

QCD corrections proceeds along the same lines as in the case of squarks and gluinos. The strong coupling and the parton densities have been defined in the $\overline{\rm MS}$ scheme with 5 light flavors contributing to their scale dependences, while the stop masses are renormalized on-shell. The QCD corrections increase the

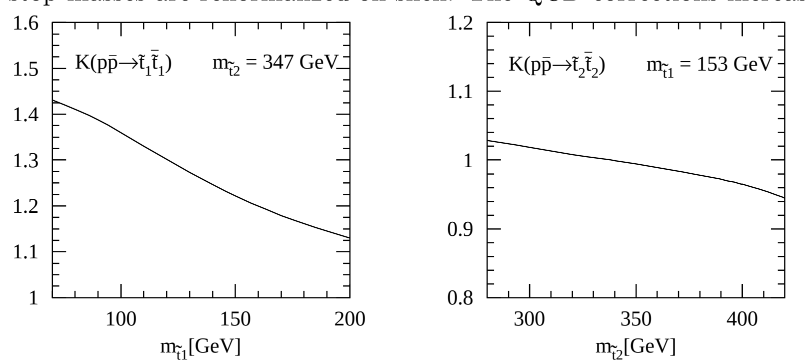

Figure 6: *K factor of the light stop production cross sections at the upgraded Tevatron [$\sqrt{s} = 2$ TeV]. Parton densities: CTEQ4L (LO) and CTEQ4M (NLO) with $Q = m_{\tilde{t}_1}$. Top mass: $m_t = 175$ GeV.*

cross sections by up to about 40% [see Fig. 6] and thus lead to an increase of the extracted stop masses from the measurement of the total cross section. Moreover, as in the squark/gluino case the scale dependence is strongly reduced [see Fig. 7] and yields an estimate of about 15% of the remaining theoretical uncertainty at NLO. At NLO the virtual corrections depend on the stop mixing

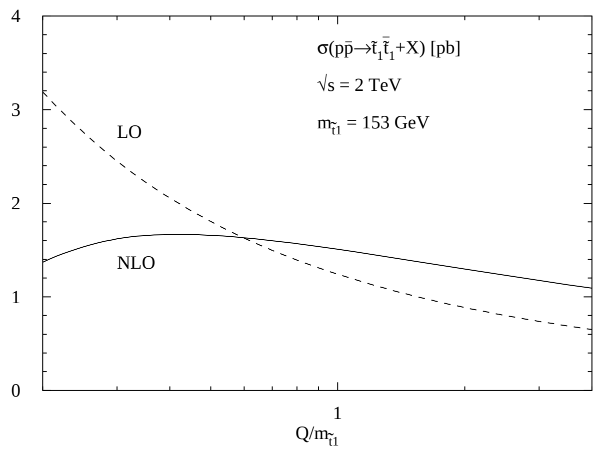

Figure 7: *Scale dependence of the total light stop production cross sections at the Tevatron in LO and NLO. Parton densities: CTEQ4L (LO) and CTEQ4M (NLO); Top mass:* $m_t = 175$ *GeV.*

angle, the squark, gluino and stop masses of the other type. However, it turns out that these dependences are very weak and can safely be neglected as can be inferred from Fig. 8.

5 Chargino and Neutralino Production

The production cross sections of charginos and neutralinos depend on several MSSM parameters, i.e. M_1, M_2, μ and tgβ at LO [5]. The cross sections are sizeable for chargino/neutralino masses below about 100 GeV at the upgraded Tevatron and less than about 200 GeV at the LHC. Due to the strong dependence on the MSSM parameters the extracted bounds on the chargino and neutralino masses depend on the specific region in the MSSM parameter space [1]. The outline of the determination of the QCD corrections is analogous to the previous cases of squarks, gluinos and stops. The resonance contributions due to $gq \to \tilde{\chi}_i \tilde{q}$ with $\tilde{q} \to q\tilde{\chi}_j$ have to be subtracted in order to avoid double counting with the associated production of gauginos and strongly interacting squarks and gluinos. The parton densities have been defined with 5 light flavors contributing to their scale evolution in the $\overline{\mathrm{MS}}$ scheme, while the t-channel squark masses have been renormalized on-shell. The QCD corrections enhance the production cross sections of charginos and neutralinos by about 10–40% [see Fig. 9]. The LO scale dependence is reduced to about 10% at NLO [see Fig. 9], which signalizes a significant stabilization of the thoretical prediction

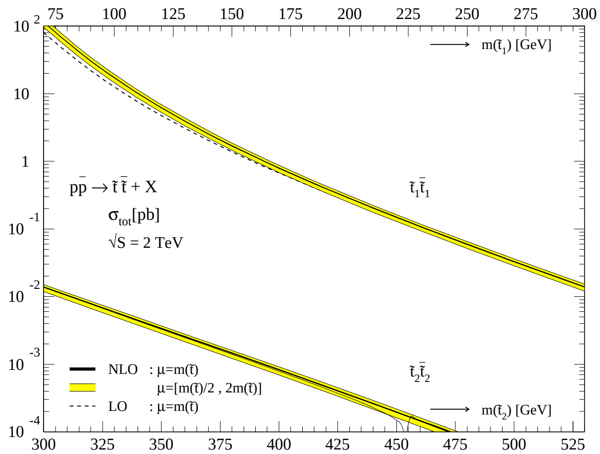

Figure 8: *Production cross sections of the light and heavy stop states at the Tevatron at LO [dashed] and NLO [solid]. The thickness of the NLO curves represents the dependence of the cross sections on the stop mixing angle and the squark and gluino masses. The shaded NLO bands indicate the theoretical uncertainties due to the scale dependence within* $m_{\tilde{t}}/2 < \mu < 2m_{\tilde{t}}$. *Parton densities: CTEQ4L (LO) and CTEQ4M (NLO); Top mass:* $m_t = 175$ *GeV.*

for the production cross sections [4]. The dependence of the chargino/neutralino production cross sections on the specific set of parton densities ranges at about 15%.

6 Conclusions

In this work we have reviewed the status of SUSY particle production at hadron colliders at NLO. Most QCD corrections to the production processes are known, thus yielding a nearly complete theoretical status. There are especially large QCD corrections to the production of gluinos, which significantly increase the extracted bounds on the gluino mass from the negative search for these particles at the Tevatron. In all processes, which are known at NLO, the theoretical uncertainties are reduced to about 15%, which should be sufficient for the upgraded Tevatron and the LHC[¶].

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[¶] The computer code PROSPINO [8] for the production of squarks, gluinos and stops at hadron colliders is available at http://wwwcn.cern.ch/∼mspira/. The NLO production of gauginos and sleptons will be included soon.

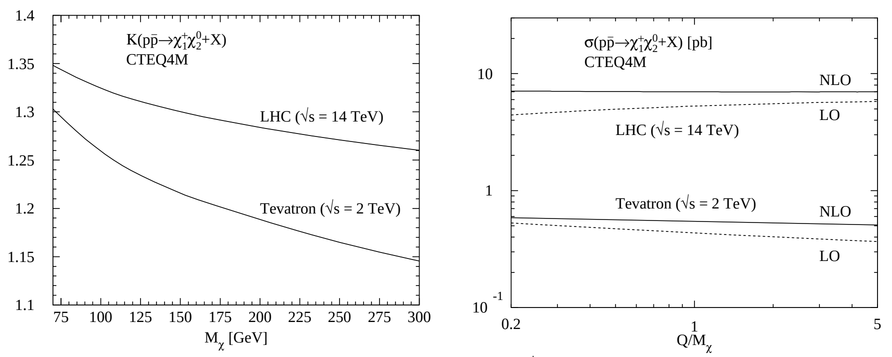

Figure 9: *K factor and scale dependence of the $\tilde{\chi}_1^+\tilde{\chi}_2^0$ production cross section at the Tevatron and LHC. Parton densities: CTEQ4L (LO) and CTEQ4M (NLO) with $Q = m_{\tilde{t}_1}$. Top mass: $m_t = 175$ GeV; SUGRA parameters: $M_0 = 100$ GeV, $A_0 = 300$ GeV, $tg\beta = 4$, $\mu > 0$.*

98 for the pleasant atmosphere during the symposium.

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